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SATELLITE ATTITUDE DETERMINATION:

DIGITAL SENSING AND

ON-BOARD PROCESSING

BY

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SUMMARY

This paper discusses in general the attitude determination problem for spin stabilized satellites using a digital aspect sensor system, and describes in some detail attitude determination systems used and to be used on several NASA satellites.

The paper consists of a description of the digital solar aspect sensor, and a discussion of the on-board data storage and data processing systems. The particular attitude determination systems discussed include those flown on Explorer X, XII, XIV, and XV, as well as those to be flown on the Atmospheric Structures Satellite (S-6), the Relay Satellite, and the Interplanetary Monitoring Probe (IMP). Some unusual data are presented, and future system possibilities are examined.

INTRODUCTION

The problem of attitude determination is the problem of defining the angular relationships between two coordinate systems, one a coordinate system fixed in some reference space and the other a coordinate system fixed in the spacecraft. There are, of course, six degrees of freedom of a spacecraft coordinate system with respect to a reference system. Three of these concern the translational motion of the center of mass of the spacecraft. The problem of measuring this translational motion is an exercise in orbit or trajectory calculations. The remaining three degrees of freedom concern the rotational motion of the spacecraft about its center of mass. The measurement of this rotational motion is called attitude or aspect determination. It is the aspect determination problem which will be dealt with here—in particular, the determination of the aspect of a rotating spacecraft by means of a digital aspect sensor.

DIGITAL ASPECT SENSOR

The digital aspect sensor consists of a number of photo-duo-diodes placed behind a light mask with slit openings as shown in Figure 1 (a).

Opaque separators are situated between the photo-duo-diodes so that each photo-diode "sees" only the portion of the light mask directly in front of it. The slits and photo-diodes are so aligned that each photo-diode has a fan-shaped field of vision lying in a plane parallel to the field of vision of the other photo-diodes. Since this sensor can be designed to detect either the sun or the moon, which are for all practical purposes point sources at infinity, these parallel planes can be assumed to be a single plane. If the sensor is rotated about a vertical axis in this plane, the fan field of vision of the diodes will sweep out a solid angle. When the fan crosses the solar disk, the sensor presents a binary word to the output terminals in parallel read-out. This word is the address of the particular fan segment which swept across the sun; hence it gives a measure of the angle between the vehicle spin axis and the sun vector. The binary address word must then be encoded into a format suitable for transmission. The accuracy of this digital measurement depends, of course, on how many binary sensors are used. A fan field of view can be quantized into as many as $2^n - 1$ segments when there are N binary sensors. A Gray Code system[2] shown in Figure 1 (b)

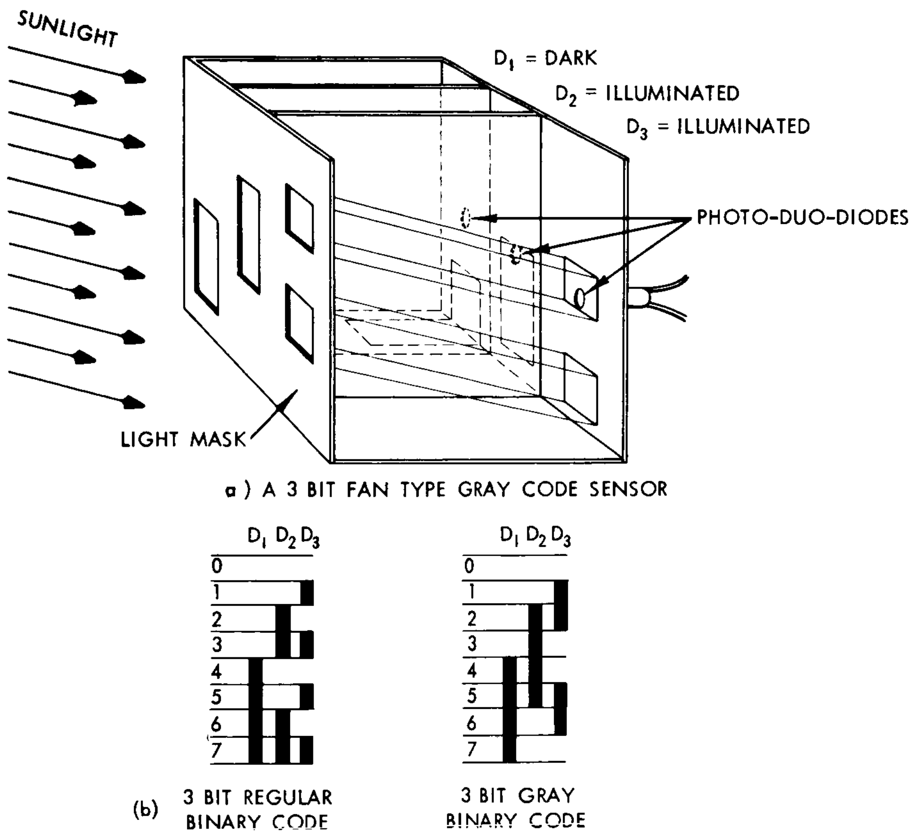

Figure 1—Schematic representation of a digital solar aspect sensor and a Gray code light mask.

is used instead of the regular binary code. This is because the Gray Code requires a decision from only one sensor for each transition between quantized segments. The regular binary code often requires simultaneous decisions from several diodes, making possible erroneous readings in the transition regions.

In a spinning satellite problem the exact time that the fan crosses the solar disk is also sometimes an important parameter. This time must be related to some known time standard and this relationship remembered, encoded, and presented to the transmitter. In various vehicles using various telemetry formats, this problem naturally has different solutions.

Since there are three degrees of rotational freedom of a rigid body in a force free field, it would be expected that in addition to the sun angle and time of appearance, at least one other parameter would need to be measured in order to completely and uniquely solve the aspect problem. Indeed this is the case.

Since to the digital sun sensor the sun is for practical purposes a point source, the vector from the satellite to the sun is an axis of symmetry. This means that loci of the spin axis is a cone whose axis is the sun vector and whose half-angle is the angle measured by the digital sun sensor, namely the angle between the spin axis and the sun vector. In order to complete an unambiguous calculation of the position of the satellite spin axis, a measurement must be made on another body which is not coincident with the satellite sun axis of symmetry. This may be done by measuring the direction to the earth or the moon. This measurement may be performed in various ways. Two methods described in this paper are the use of a narrow beam horizon detecting telescope and the use of a wide angle moon detecting fan. These detectors, of course, must deal with such problems as phases of the moon, partial illumination of the earth disk, cloud cover, altitude variation, type of orbit, etc. The type of detector and the mounting arrangements must often be tailored to fit a particular set of circumstances.

A useful tool in visualizing the action of the digital sensor in the aspect determination problem is the concept of the celestial sphere shown in Figure 2. The digital fan can be visualized as a series of numbered light channels sweeping the sky. The celestial sphere is, of course, an inertial reference system. The sun is conceptualized as a 0.5 degree disk moving in the ecliptic on the celestial sphere approximately one degree per day. The moon is a 0.5 degree disk traversing its orbit once

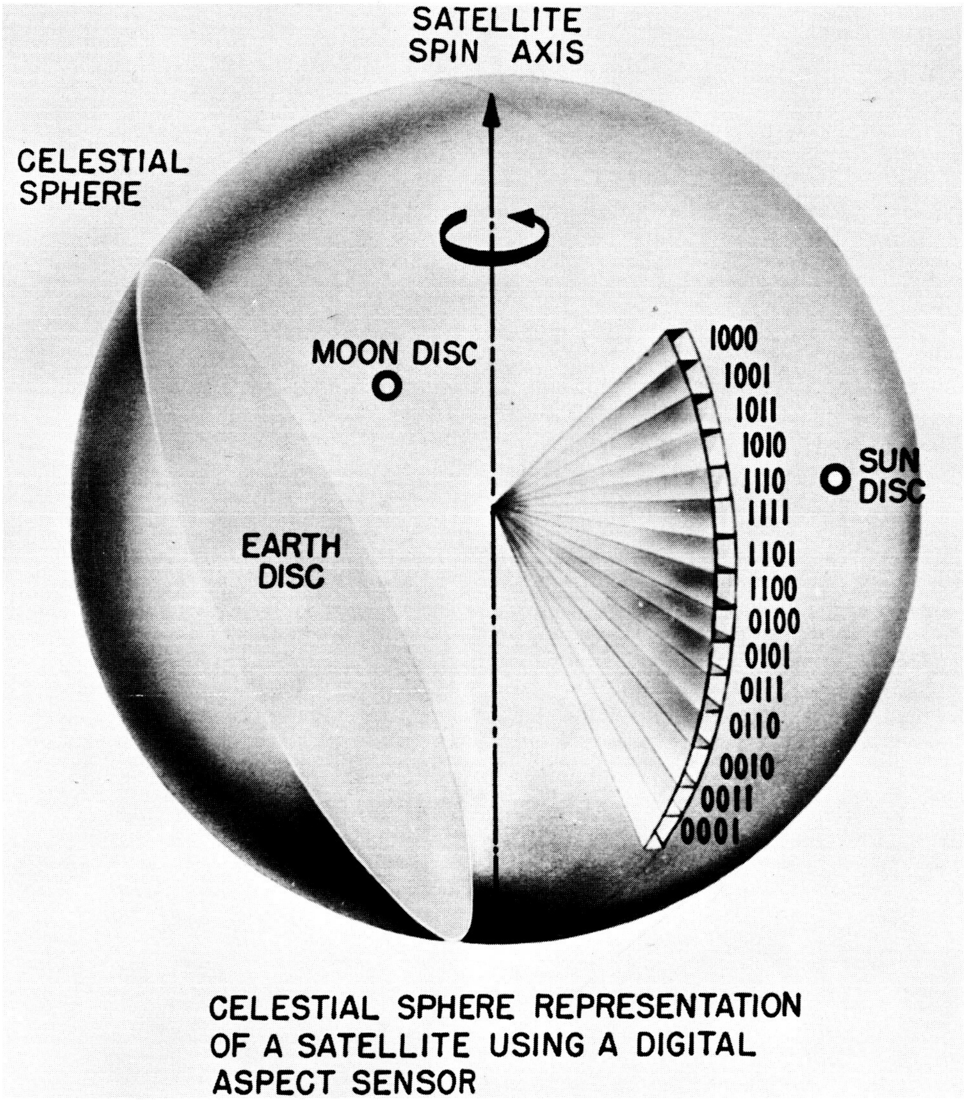

Figure 2–Celestial sphere representation of the satellite attitude determination problem using a digital sensor.

per month, and the earth a large disk covering a large part of the celestial sphere and moving completely around the sphere once per orbit of the satellite. The apparent size of the earth's disk is, of course, a function of the satellite altitude. At zero altitude the earth disk covers 2π steradians or half the celestial sphere. At satellite altitudes the earth naturally appears somewhat smaller. The digital solar aspect fan sweeps across the celestial sphere producing a signal output whenever it crosses the sun disk. Digital sensors have also been designed which can detect the moon's disk at night when the earth disk covers the sun.

The specific satellite aspect systems to be discussed will be mentioned in order of increasing complexity. The most simple system is that used on the Relay communications satellite. It measures only one parameter, the angle between the spin axis and sun vector. This sensor system consists merely of a digital sun sensor combined with an additional slit sensor which is set so as to sweep across the sun about 10 degrees of rotation before the digital field of view crosses the sun. A bistable flip-flop is connected to each of the digital sensor outputs. When the slit field of view sweeps the sun, it resets all the bi-stable flip-flops to a "zero" state. When the digital sensor crosses the sun, it reads a binary word into the flip-flops. The outputs of these flip-flops are then sampled in parallel at convenient rate by the telemetry system.

A sample of the data received from Relay is shown in Figure 3. The vertical bars refer to the width of the activated quantized fan segments. The change of the angle between the spin axis and the sun vector is due primarily to the apparent motion of the sun on the celestial sphere. Note that a smooth curve which lies within the quantized

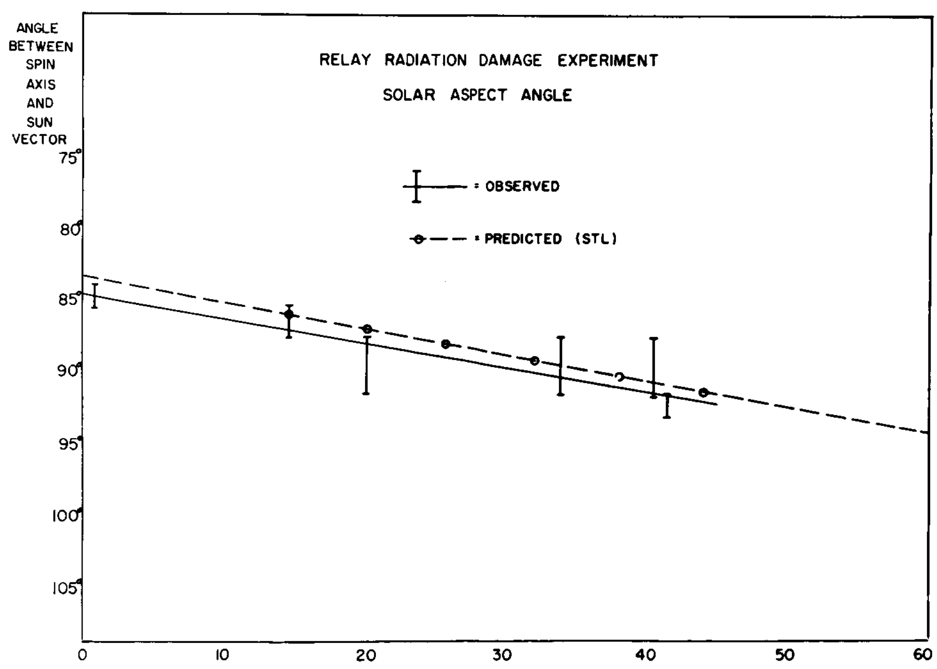

Figure 3–Spin axis vector data from Relay satellite showing motion of sun across sensor transition.

segments can be drawn. Since the edges of the quantized segments are accurately calibrated and data are plotted over many days, the angle between spin axis and sun can be measured much more accurately than the nominal quantization accuracy.

THE S-3 SATELLITE SERIES

The attitude determination system used on the S-3 energetic particles satellite series is more complex. This series includes Explorer XII, XIV, and XV.

The S-3 series digital sun sensor is shown in Figure 4 (a). This sensor is made from six glass prisms similar to the one shown in Figure 4 (b). Thus it has a 180-degree fan field of view. The sensor is then mounted so that, as the satellite rotates, the quantized fan field of view sweeps the entire sky.

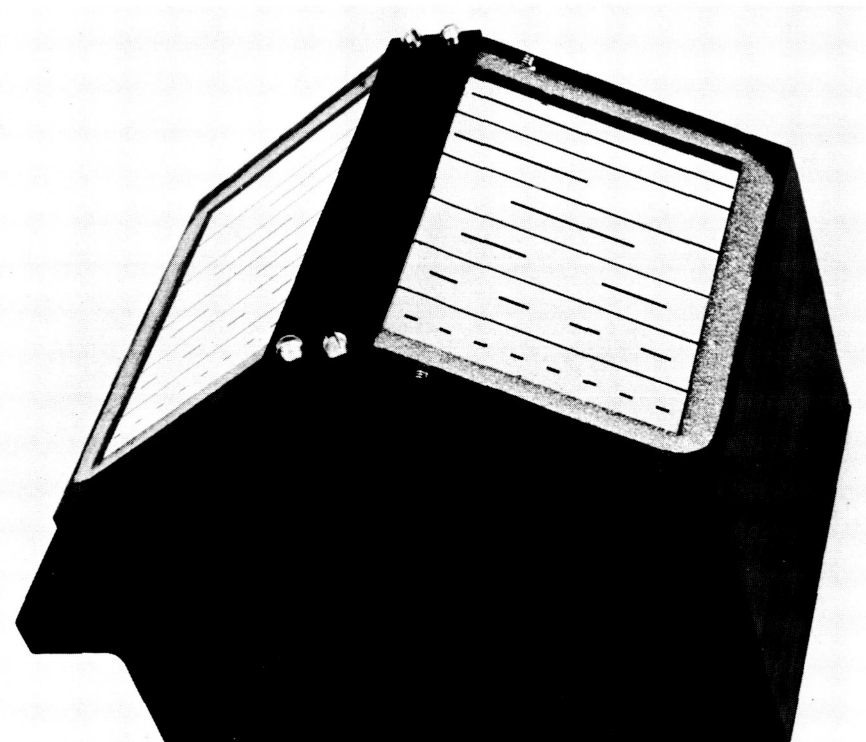

Figure 4—S-3 type digital solar aspect sensor with a 180 degree fan field of view quantized into 63 parts.

On the S-3 satellite series the exact time the digital fan crosses the solar disk is measured as well as the angle between the spin axis and the sun. A third parameter needed for a unique aspect solution is obtained from magnetic field sensors. On the S-3 type of satellites the information rate is relatively slow and the efficient use of telemetry bandwidth is therefore important. For example, on Explorer XII the telemetry frame rate samples the aspect system approximately five times per satellite revolution. In order to get more accurate rotation information, the state of the telemetry sequencer at the time of occurrence of a sun appearance signal is remembered on three flip-flops while the angle information is stored on six magnetic cores. This information is then slowly fed to the PFM[3] telemetry system three bits at a time. The information on the magnetic cores is transferred to the three flip-flops as a part of the read-out process. The flip-flops are connected directly to an eight-level PFM oscillator which is gated "On" once per telemetry frame.

A photograph of the signal conditioning circuitry is shown in Figure 5. Supermalloy cores are used as the magnetic memory elements. Cores are also used as synchronizing elements. Four complementary flip-flops are shown in the lefthand side of the picture. Three of these are tied to the telemetry, while the fourth is switched to allow read-out of the cores. This entire system including the digital sensor consumes less than three milliwatts of power.

Figure 6 shows data taken from Explorer XII during despin and separation. At $03^h\ 51^m\ 14.6^s$ the despin yo-yo's were released, and the rotation rate dropped from 202.1 rpm to 45.83 rpm. Since the two yo-yo weights did not separate simultaneously, a precession coning of about 5.5° half-angle was induced. This motion continued for approximately nine minutes until $03^h\ 59^m\ 50^s$. At this time separation of the satellite from the third state rocket casing and erection of the solar paddles took place. The rotation period then dropped to 27.803 rpm and the precession coning decreased in amplitude to about one degree half-angle. However, because of the change in inertia moments, the precession rate increased from 6.8 rpm to 35.31 rpm. The precession amplitude damped out as expected in about 48 hours, but after several weeks a very unexpected phenomenon was observed. The rotation rate increased! This phenomenon was apparently not related to forces of terrestrial origin, since during an entire orbit the increase in rotation rate was observed to be independent of altitude. An explanation of this phenomenon was found rather in solar radiation pressure acting on the solar paddles. The solar paddles were orientated unsymmetrically in propeller fashion.

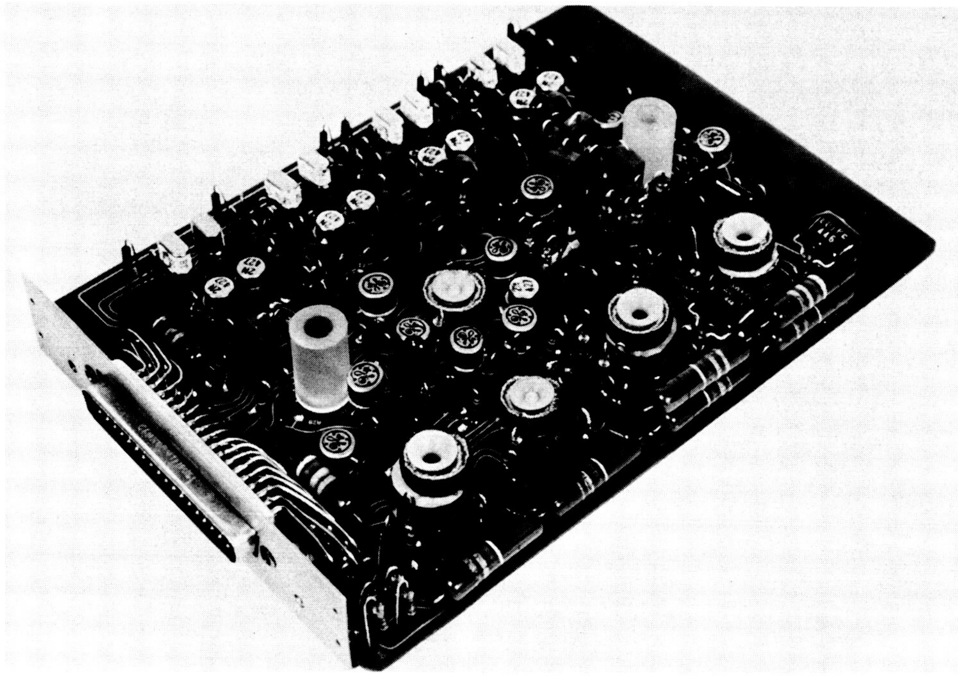

Figure 5–Data processing circuitry for the S-3 satellite series.

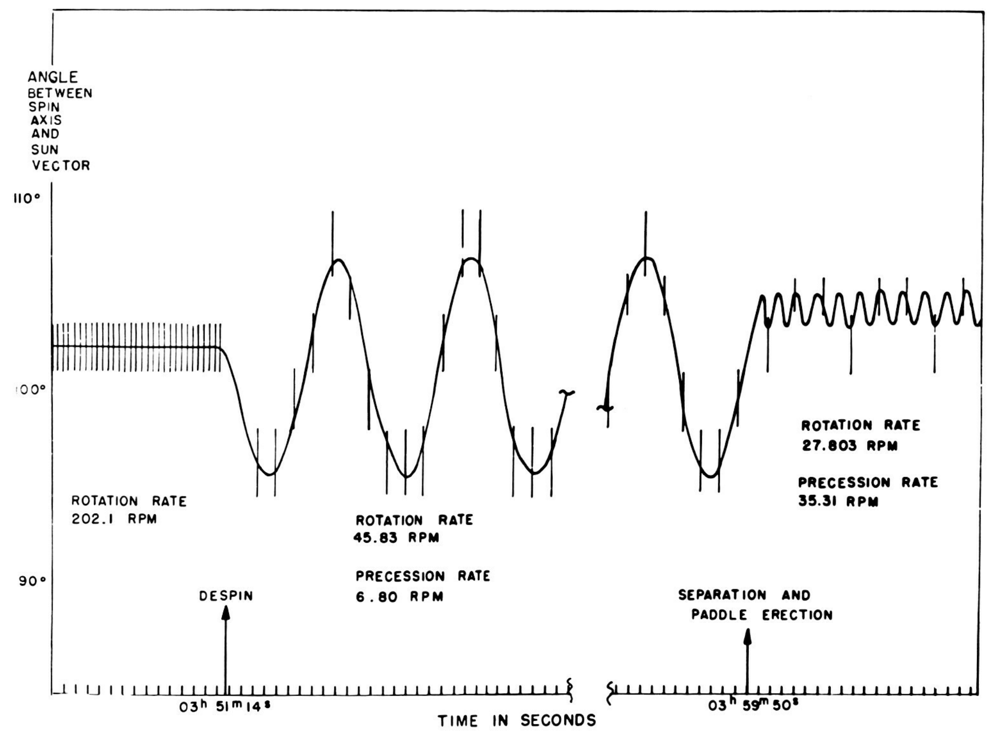

Figure 6–Aspect data from Explorer XII during despin and separation.

Sunlight falling on the paddles thus produced a net torque about the center of mass of the satellite in the proper direction and of sufficient magnitude to account for the observed effect.

Another interesting and rather surprising phenomenon was observed in Explorer XIV. On this satellite the rotation rate increased because of solar radiation pressure, as was by then expected; and in addition the amplitude of the precession coning, after initially decreasing, began to increase sharply and unexpectedly. The history of the Explorer XIV precession coning is shown in Figure 7. This precession amplitude finally reached a plateau around November 5, and on December 5 began to decrease. This erratic behavior has been tentatively explained as caused by and interaction between the magnetic field of a pulse solenoid aboard the spacecraft and the magnetic field of the earth. The abrupt beginning and disappearance of this precession coning has

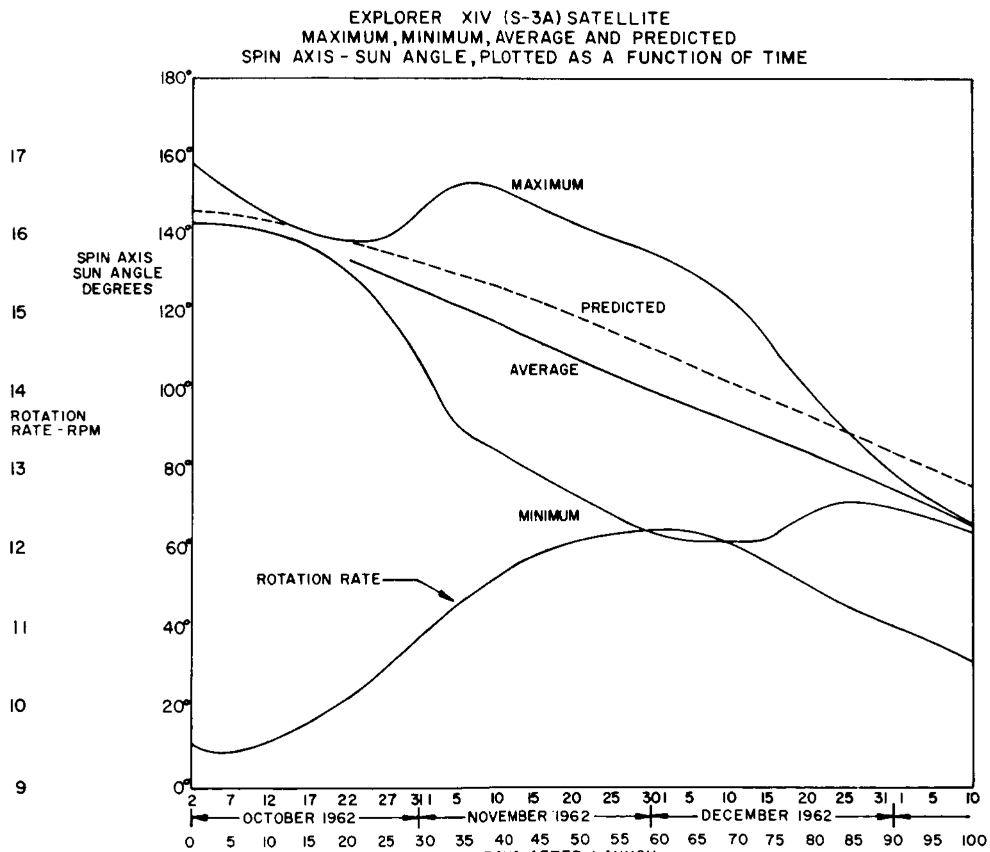

Figure 7—Precession angle and spin rate history of Explorer XIV from launch to January 10, 1963.

not been fully analyzed as yet but is presumed to be caused by a resonance between the spacecraft rotation rate and the solenoid pulse repetition rate. The increase in the rotation rate early in the spacecraft life and subsequent decrease in rotation rate at a later date is easily explained by the solar pressure propeller theory. Early in flight the angle between the spin axis and the sun was larger than 90 degrees such that the solar paddle propeller was of the proper sense to increase the rotation rate. At 90 degrees between spin axis and sun, the net torque was zero and the rotation rate held constant. At angles less than 90 degrees, the propeller sense was such that the rotation rate was decreased by radiation pressure.

This large angle of precession coning could have proved disastrous to many of the directional sensitive experiments aboard Explorer XIV. However, the digital solar aspect sensor has the distinct advantage of producing data easily digested by automatic data processing systems. There is now operational at Goddard Space Flight Center an automatic aspect data reduction computer program which can reconstruct the complete history of the Explorer XIV precession and spin motions.

ATMOSPHERIC STRUCTURES SATELLITE

The Atmospheric Structures Satellite (Explorer XVII) attitude determination system is called upon to provide a unique description of the satellite position relative to its orbital velocity-vector at any time of day or night. This requires the use of infrared earth horizon detectors in conjunction with a digital sun sensor by day and a digital moon sensor by night.

The infrared horizon detectors shown in Figure 8 have pencil beam fields of view and are mounted so that one detector looks slightly forward at 68 degrees from the spin axis and the other looks slightly aft at 112 degrees from the spin axis. Both pencil beam fields of view lie in the same plane as the digital fan. The horizon detectors produce a pulse when the pencil field of view crosses into the horizon and another pulse when it crosses out. The digital sensor shown in Figure 9 has its light mask deposited on curved glass prisms which provide an optical light gathering amplification of approximately ten over the S-3 type sensor. This sensor with sensitive amplifiers attached to the photo-diodes thus has the capability of detecting the half moon. A separate sun sensor switches off the sensitive amplifiers for daytime operation. In addition there is another sensor located in the center of the digital sensor called the sun-moon slit whose field of view is a fan which is offset by

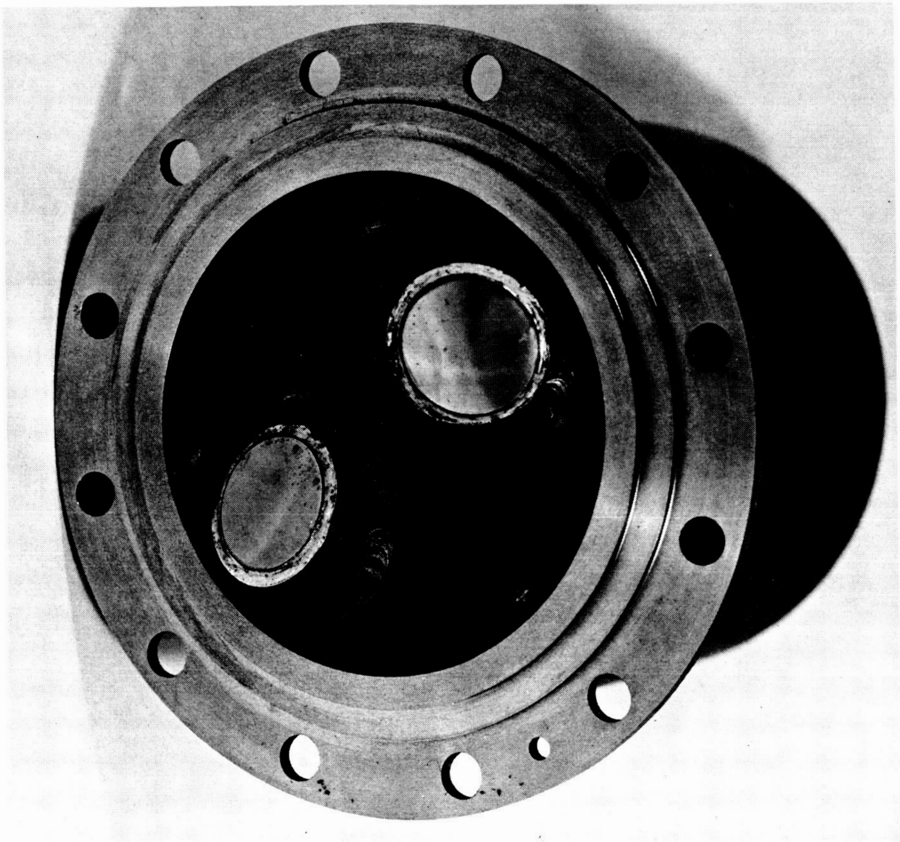

Figure 8—Infrared horizon detectors for Atmospheric Structures Satellite.

a prism so that it trails the digital sensor field of view by 45 degrees of rotation. This sun-moon slit is sensitive to the sun by day and the moon by night. Its function is to provide accurate time of appearance information for either sun or moon. The 45 degree offset of the slit field of vision prevents overloading of the available telemetry channel.

The telemetry system for the Atmospheric Structures Satellite is a PCM system and transmits aspect information on a nine bit binary word once every 20 milliseconds.

Signal processing for this satellite consists of both a memory function and a priority system also incorporated to prevent overloading of the available channel. In the case of both sun slit and earth horizon sensor inputs appearing in a single frame, the sun information is retained and the earth information rejected. There is also a similar priority setup between the two earth sensors.

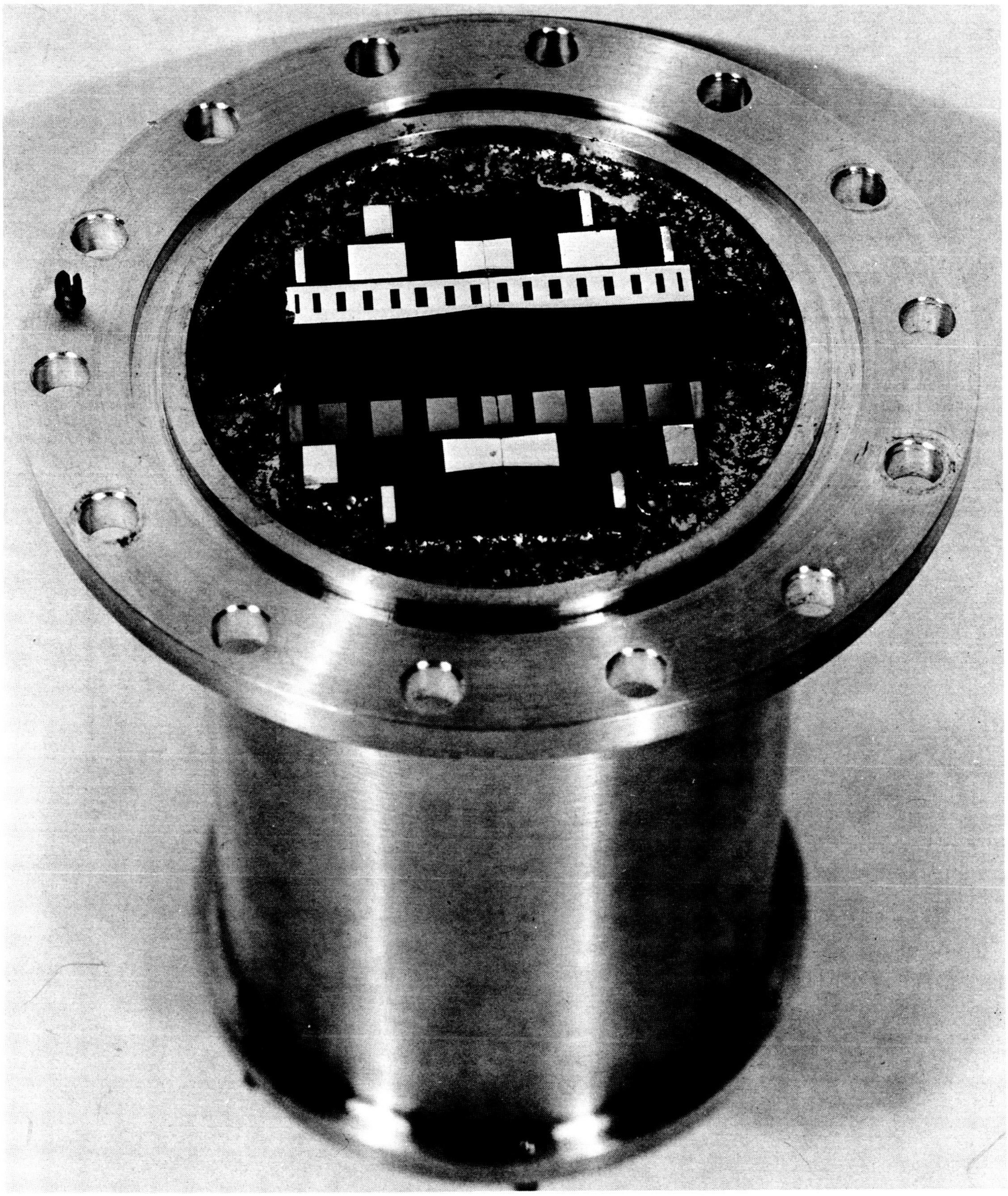

Figure 9—Sun-moon digital sensor, sun-switch and sun-moon slit sensor for Atmospheric Structures Satellite.

Figure 10 is the logical diagram of the data processor on board this satellite. Table I shows the function of the various bits. The time indicators T_1 through T_4 give a binary number which indicates how many clock pulses lie between the time when the sensor of greatest priority had an input and the time of aspect word transmission. Priority is in the order of sun-moon slit, Earth I, and Earth II. The above is best clarified by examples. The transmitted word "01001000" means that earth no. 1 had an output at time "1000" (i.e., 8 clock pulses before transmission) and no other sensor had output during the frame. "01111001" means that Earth I, Earth II, and the slit provided outputs during the frame and that the slit pulse arrived at time "1001." In this latter case

Table I

BIT	INDICATION	
A	"1" if digital sensor had an input since last aspect word transmission	
	If A a "0"	If A a "1"
B	"1" if earth sensor no. 1 had an input	"1" if moon amplifier on
C	"1" if slit had an input	"1" if least significant bit D_1 of digital sensor had an input
D	"1" if earth sensor no. 2 had an input	"1" if D_2 had an input
E	Least significant time bit T_1	"1" if D_3 had an input
F	T_2	"1" if D_4 had an input
G	T_3	"1" if D_5 had an input
H	Most significant time bit T_4	"1" if D_6 (most significant digital sensor bit) had an input

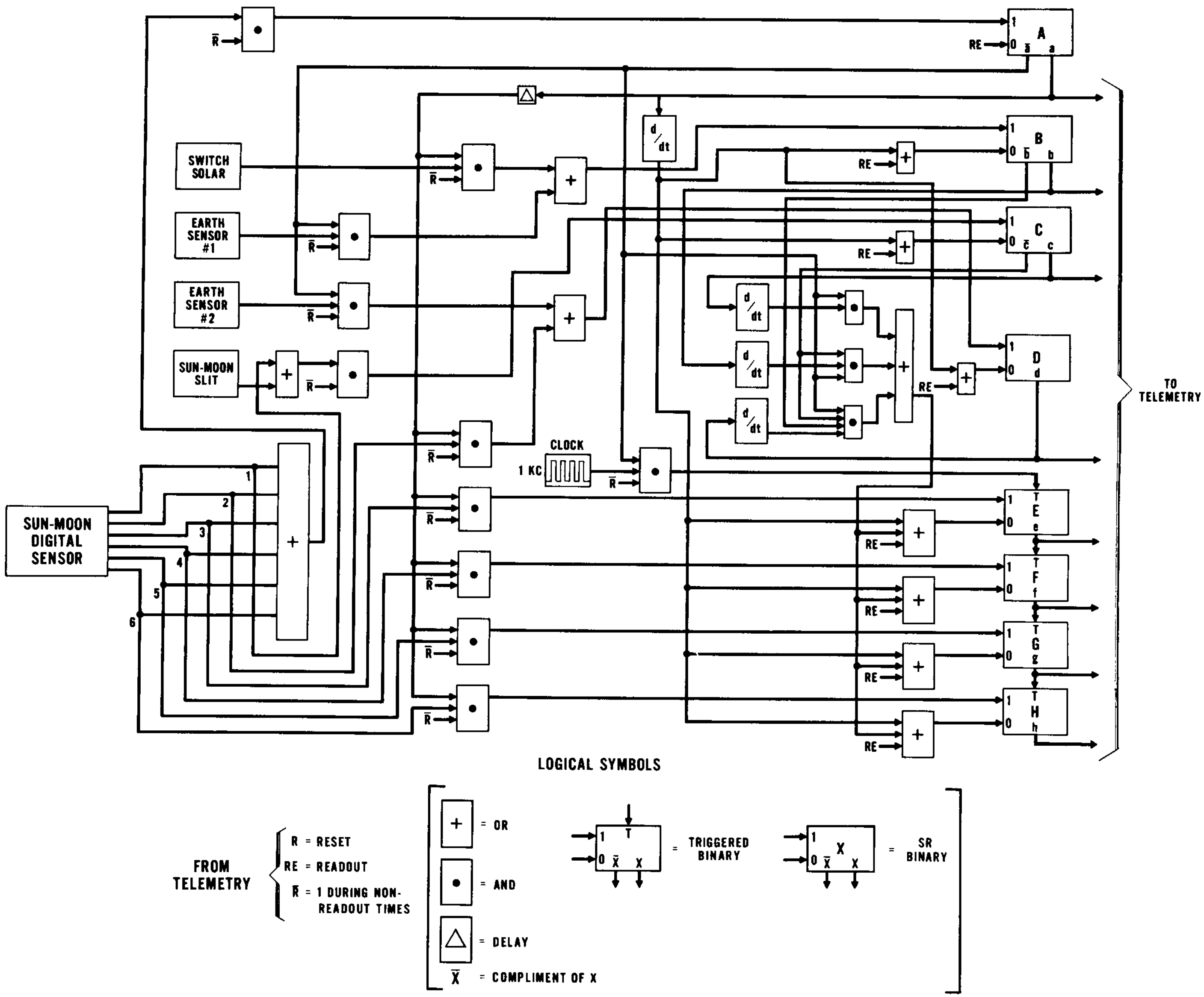

Figure 10–Logical Diagram of Atmospheric Structures data processor.

no time information is given about the earth inputs. For a case when bit A is a "1" the word "11001000" means the spin-axis moon-angle is located in quantized fan segment "001000." Power dissipation in all the circuitry required to perform this logic is less than five milliwatts.

EXPLORER X

Explorer X was launched into a highly elliptical orbit on March 25, 1961. Therefore, chronologically this is the oldest satellite discussed in this paper. Its mission was to measure magnetic fields and plasma. Explorer X attained a distance of 180,000 miles from the earth during its intended lifetime of 50 hours. The attitude determination system in this satellite was designed to (1) measure the angle between spin axis and the sun vector by means of a four-bit digital sun sensor, (2) measure the time when the digitized field of view crossed the sun, (3) remove the ambiguity of the spin axis position, and (4) measure the height of the satellite above the surface of the moon. This latter ability was incorporated because, during the planning of the project, the possibility of a launch to the moon was present.

These measurements were made with a detector which uses a standard four-bit digital sun sensor combined with a sun reset slit similar to the Relay sensor. There was also another slit sensor attached to a sensitive amplifier which was capable of sensing light from the moon or the earth. In addition there was a sun-switch sensor which opened a gate in the earth-moon amplifier output when the sensor was pointing toward the sun. The telemetry system used aboard Explorer X made available to the aspect system a five second PFM burst once every two minutes. The PFM oscillator was quantized into 16 discrete frequencies. The reset slit set the subcarrier oscillator to its lowest frequency state. Twenty degrees of rotation later, the PFM oscillator was set and held at one of its 15 other discrete frequencies by the four-bit digital solar sensor. After the satellite had rotated far enough so that the sun-switch was deactivated, control of the oscillator was transferred to the earth-moon amplifier. When the earth-moon fan slit was not illuminated, the oscillator frequency remained unchanged. However, when the earth-moon sensor viewed a bright surface, the oscillator frequency was indexed upwards every 2.5 milliseconds for as long as the bright object remained in the slit field of view. If the slit sensor still viewed the bright object when the oscillator reached its highest frequency, the next indexing pulse reset the oscillator to its lowest frequency and the indexing continued upward. The length of this counting sequence was a measure of the height of the satellite above the earth or moon. The relative position of the sun sensor reset-set sequence to the earth-moon sensor counting sequence removed the ambiguity of the spin axis position.

The length of time the earth or moon was seen could be determined to within ±2.5 milliseconds by noting the difference between the frequency before and after stepping. This was most valuable at the moon distance, as the signal to noise ratio was so poor that the stepping could not be seen. Filters, however, easily pulled out the before and after frequencies.

INTERPLANETARY MONITORING PLATFORM (IMP)

The Interplanetary Monitoring Platform is a fields and particles satellite which will have a 150,000 nautical mile apogee. Its telemetry information rate is therefore quite low.

The IMP uses a digital sun sensor nearly identical to the S-3 series sun sensor. In addition it has an earth sensor sensitive to visible light with a pencil field of view mounted so as to scan 90 degrees from the spin axis.

The data storage and read-out system on this satellite is quite different from the previously discussed systems, as there will be many revolutions of the satellite between read-out times. The method used is to sample one of these revolutions and store all of the data collected during this revolution, a total of 45 bits of information. This collection of bits will then be telemetered once every 80 seconds.

The quantities to be telemetered are: (a) ten bits of data defining the time between the sampling sync pulse and the first sun appearance in the sampling period, (b) six bits giving the angle between the spin axis and the sun at this time, (c) ten bits giving the length of time between the 1st and 2nd sun appearance (i.e., the spin period), (d) ten bits defining the time at which the earth sensor pencil is pointed midway between horizon intersections on the earth disk, and (e) nine bits defining the azimuthal angle between the sun and the maximum magnetic field intensity as determined by a flux gate magnetometer sensor. This last quantity was included to facilitate reduction of magnetometer data. Near perigee, however, the situation can be reversed and magnetic data used as a parameter in aspect determination.

The data processing circuitry consists of a much greater number of memory units than any of the previously discussed systems. The data processor used a clock running at a 200 cycle rate indirectly generated by a crystal that controls the satellite encoder. The logic in this circuitry controls the flow of information to the various memory elements. It turns counter chains on and off as determined by the input signals, while the binary digit sun angle memories are inhibited after receipt of one sun input.

The specific logic to determine the midpoint between the two horizon intersections may be of interest. Here the problem is to transmit information only about the midpoint between two pulses. The time of occurrence of the individual pulses is of no interest. Starting at the sync time a counter is indexed at 200 cps until the "horizon in" pulse occurs. It then is indexed at half this rate until the "horizon out" pulse occurs. The counter at this time contains the same number of counts as if it had been merely indexed at the original 200 cps rate from the sync time until midpoint between the two horizon pulses. The actual circuitry inserts a pre-stage on the counter chain at the time that the "horizon in" pulse occurs and terminates all counting when the "horizon out" pulse occurs.

The complete data processing circuitry is shown in Figure 11. The small upright devices are small printed circuit boards upon which have been mounted Texas Instruments integrated circuits. These small boards are in turn mounted on a larger board. The small boards are shown unmounted in Figure 12. The use of integrated circuitry allowed this complete circuit to be mounted on one large printed circuit board. Three large boards would have been required if only conventional circuitry had been used. In Figure 12 the upper and lower two cards are ten stage counters. The card with six solid circuits is the digital sensor memory. The three solid circuits on one board in the center is the logic for the sun inputs, while the board with the five solid circuits is the earth input circuitry.

The use of integrated circuits has been found quite satisfactory. The principal disadvantage over using conventional circuitry is the increased power usage. To overcome this, the power to the precessor is turned off during 80 percent of the time that no data are being collected.

ADVANCED SYSTEMS

In the data processing area it is obvious that for a stable spacecraft too much data are being transmitted. As spacecraft travel farther from

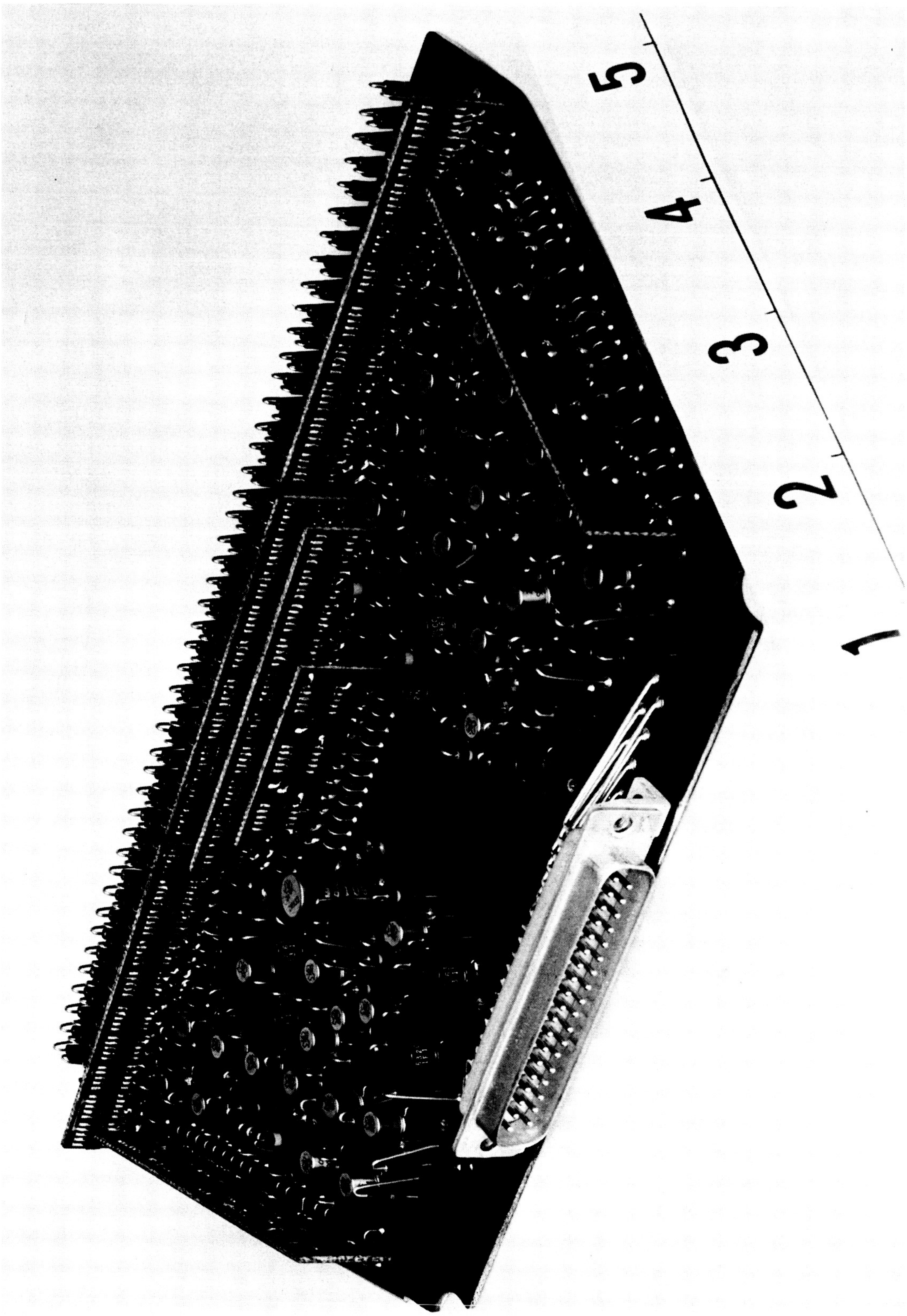

Figure 11—IMP optical aspect data processor.

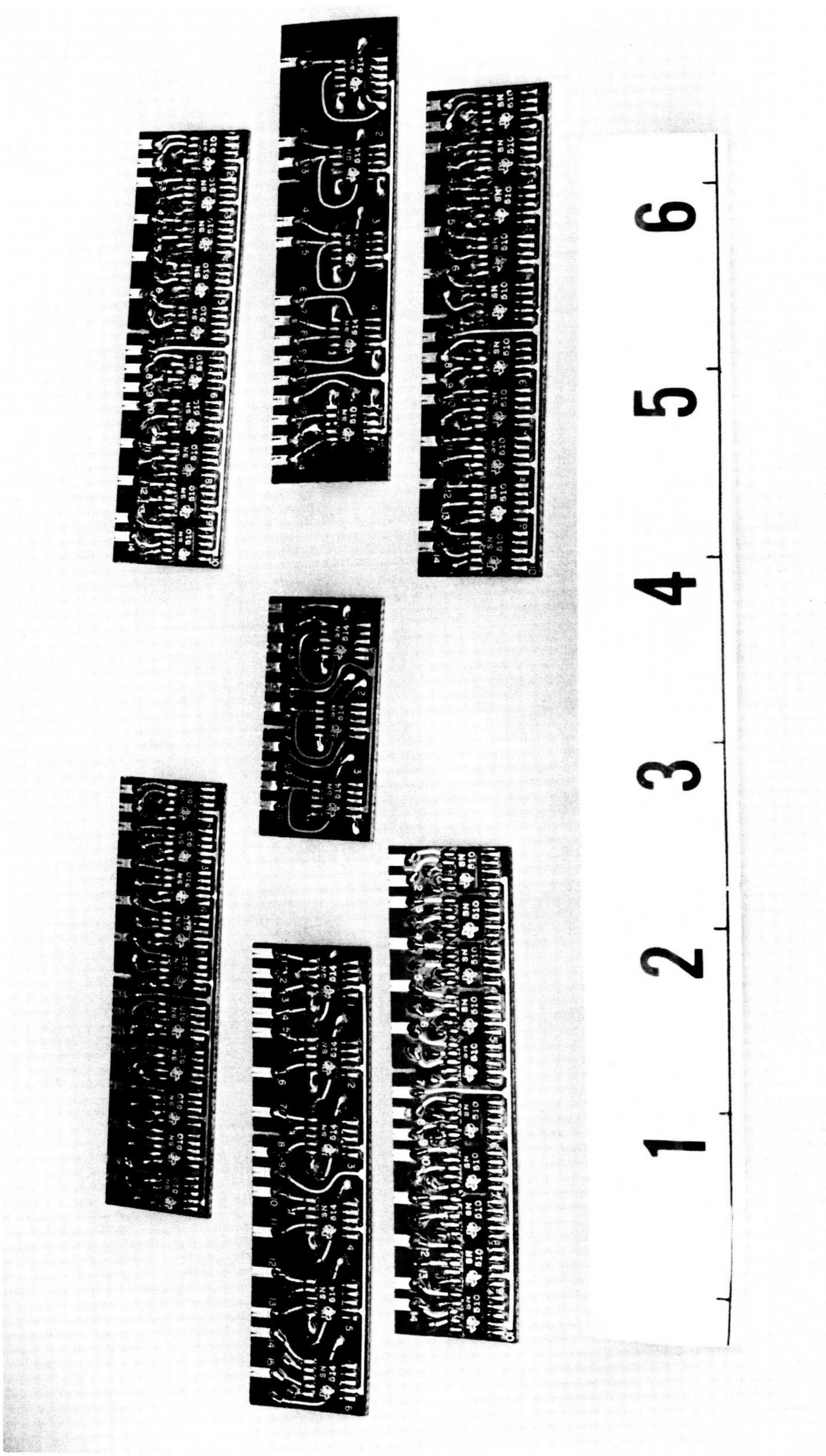

Figure 12–Submodules on which integrated circuits are mounted.

the earth data transmission rates will be reduced and the transmission of data will become more and more costly. On future spacecraft, experiments may be internally triggered or timed from sun or earth signals, so that the number of strictly aspect bits can be reduced an order of magnitude. For spacecraft well removed from the earth, the use of stars as reference bodies appears to be the most practical approach, even for spin stabilized spacecraft. Here even more extensive uses of on-board processing will be necessary to eliminate the transmission of superfluous information.

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